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MatACDC - An Open Source Software Tool for Steady-State Analysis and Operation of HVDC Grids

J. Beerten, R. Belmans

Department of Electrical Engineering, Division ELECTA & EnergyVille, University of Leuven (KU Leuven)
Kasteelpark Arenberg 10 3001 Heverlee-Leuven, Belgium, email: jef.beerten@esat.kuleuven.be

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Abstract

With the increased interest in HVDC grids and their steady-state interactions with existing AC systems, there is a growing need for the development of tools to study the power flows in these systems. In this paper, we present MATACDC, an open source software for the analysis of hybrid AC/DC systems. The tool is available for everyone to download and allows to study the power flows in complex hybrid AC/DC systems. Incorporation of different converter control strategies enables the study of their steady-state impact for different contingencies, such as line outages or converter outages. MATACDC has been fully integrated with the power flow routines of MATPOWER, the open source MATLAB toolbox for solving AC system power flow and optimal power flow problems. A case study of the CIGRE B4 DC grid test system shows that the tools can be used to analyse complex hybrid AC/DC systems.

1 Introduction

High Voltage Direct Current (HVDC) transmission, and especially the Voltage Source Converter (VSC) variant, is gaining a lot of interest in the power industry. The technology is considered more and more for future grid reinforcements and is currently being proposed as a technological candidate to build future offshore grids to interconnect offshore wind farms. In Europe, these developments could lead to the construction of a meshed HVDC grid, often referred to as the supergrid [1].

The operation and analysis of different HVDC connections, future multi-terminal schemes and meshed HVDC grids, in combination with the existing AC infrastructure, poses major challenges due to different system characteristics and control methodologies. As these topics will be the subject of research in the years to come, there is a need for software tools to study the interactions within HVDC grids, the coordination of different HVDC systems, as well as with the interactions with the AC systems.

This paper presents the new open source hybrid AC/DC power flow software MATACDC. MATACDC is a MATLAB-based program that enables the analysis of different AC and DC systems and their steady-state interactions. The program uses a sequential power flow routine [2] to solve the AC and DC system equations and has been seamlessly integrated with the AC power flow routines of MATPOWER.

The tool is freely available online and the code is fully documented [3]. The software comes with a number of built-in control and converter models, but at the same time, it has been conceived with user-defined extendibility options in mind. The tool is thus targeted towards researchers and students to study new system control schemes, but it can also serve utility engineers to study such future power systems. The software has been developed with the analysis of different AC and DC systems and their steady-state interactions in mind and is therefore ideally suited for operational studies. Amongst others, the routines can be used to study the effects of contingencies such as converter and line outages and the system-wide effects of the corresponding converter control actions on the power flows in the AC and DC systems.

This paper discusses the HVDC system representation, thereby accounting for various converter control options, as well as the functional layout of the software and examples for the addition of user-defined functions (e.g. control mode representation or the modelling of new components). It is discussed how different converter control strategies are easily represented in the software. The implementation of the CIGRE B4 DC grid test system in the software is discussed and a case study with two different system control structures is presented.

2 Design philosophy

In the design phase, as much care as possible has been taken to integrate the program seamlessly with MATPOWER, a power flow and optimal power flow program in MATLAB [4]. The package has been fully integrated with the existing AC power flow routines from MATPOWER, while keeping the MATPOWER original source code unaltered.

MATACDC shares the same philosophy as MATPOWER, and *MatDyn* [5], a MATLAB-based open source transient stability program for AC systems: "It is intended as a simulation tool for researchers and educators that is easy to use and modify." [6]. The program has been designed such that MAT-

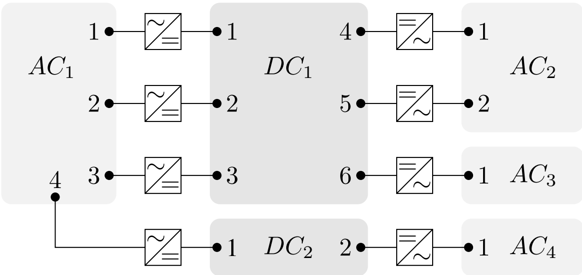


Fig. 1: Interconnected hybrid AC/DC system.

POWER users can easily use MATACDC due to a similar program structure and many similarities, such as

- MATACDC uses the MATPOWER power flow data case files.
- MATACDC uses similar DC system case files, with three distinctive data matrices, `busdc`, `convdc` and `branchdc`, to store the information on the DC system and the interconnection with the AC system. The choice of these three data matrices is analogous to the subdivision in the `bus`, `gen` and `branch` matrices in MATPOWER's AC power flow data input.
- Similar to the power flow command `runpf` in MATPOWER, MATACDC uses the `runacdcpf` command to run an AC/DC power flow:
  ```
  >> runacdcpf(casefileac,casefiledc);
  ```
  in which `casefileac` is the MATPOWER AC power flow data case file and `casefiledc` the MATACDC DC power flow data case file.
- MATACDC also stores the results in MATLAB structs:
  ```
  >> [mpc, mpcdc] = runacdcpf(...);
  ```
- Individual data elements in the MATACDC results can be accessed using the named column indices:
  ```
  >> define_constantsdc;
  >> Vdc = mpcdc.busdc(:,VDC);
  ```
  In this example, the voltages at the different DC buses are stored in the vector `Vdc`.
- MATACDC uses an option vector similar to MATPOWER. For example, printing the output can be suppressed by:
  ```
  >> opt = macdcoption;
  >> opt(13) = 0;
  >> [mpc, mpcdc] = runacdcpf(...
             casefileac,casefiledc,opt);
  ```
  Similarly, converter voltage and current limits can be enforced by changing the option vector:
  ```
  >> opt(10) = 1;
  ```

As depicted in Fig. 1, MATACDC can be used to study complex interconnected systems with an arbitrary number of AC

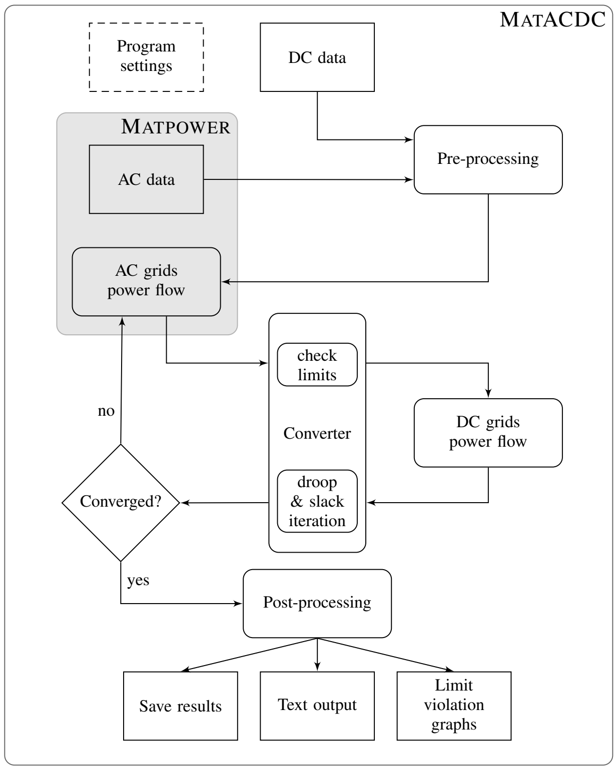


Fig. 2: MATACDC program flow.

and DC systems. For convenience, the AC and DC bus numbers forming the interconnections to respectively the DC and the AC network have been sequentially numbered, starting from 1. Neither the AC nor DC systems have to be limited to these interconnected buses. In this example, AC systems 3 and 4 only share one converter with respectively HVDC systems 1 and 2. These AC systems can represent relatively small systems, e.g. island systems or (offshore) wind farms connected to the offshore systems, but they can also represent larger AC systems that only have one interconnection with the other AC systems in the grid.

3 Program layout

To solve the power flow equations for AC/DC systems, either a sequential [2] or combined power flow algorithm [7] can be used. Internally, MATACDC uses the sequential approach to determine the power flows in the AC and DC systems, meaning that the program solves the AC/DC power flow by iterating between the AC systems and the DC systems. Doing so, the DC system quantities remain unaltered during the AC system power flow, and vice versa. The advantage of using a sequential approach is that the models can relatively easy be combined with existing AC power flow software, in this case the MATPOWER power flow package. Fig. 2 shows the program flow structure. During the iteration, converter limits can be enforced and the corresponding representation of the converters in the power flow routines is updated accordingly.

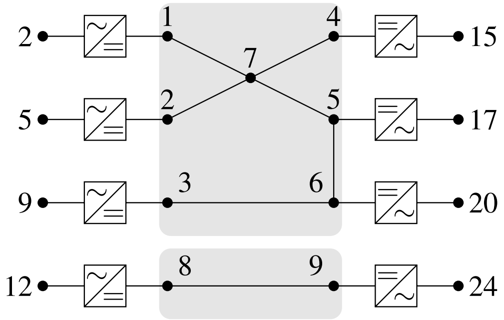


Fig. 3: DC system bus numbering: example

4 System input data format

MATACDC uses three distinctive data matrices to store the information on the DC system and the interconnection with the AC system. The choice of these three data matrices is in analogy with the subdivision in the `bus`, `gen` and `branch` matrices in AC power flow. These three data matrices are:

- `busdc` matrix: Contains all DC bus data (e.g. bus numbers, active power withdrawals, voltages, ...)
- `convdc` matrix: Contains all converter station data (e.g. loss data, impedance values, status, control modes, ...)
- `branchdc` matrix: Contains all DC branch data (e.g. line resistance, bus numbers, ...)

This flexible definition of the DC system allows a generalised implementation of DC systems with multiple connections to different AC power systems as well as DC buses without connections to the AC system.

4.1 DC buses

Each DC bus can either have a corresponding AC bus or can not be connected to the AC system, as shown in Fig. 3. This example shows a topology similar to the one from Fig. 1, but with an arbitrary AC bus numbering and a consecutive DC bus numbering in the two DC systems. The system also includes a DC bus without a connection to the AC grid (DC bus 7). The representation of the AC bus numbers, DC bus numbers and the DC grid index in the `busdc` matrix for this example is given by

```
%%          BUSDC_I   BUSAC_I   GRIDDC   ...
busdc = [      1         2         1     ...;
               ⋮         ⋮         ⋮
               6        20         1     ...;
               7         0         1     ...;
               8        12         2     ...;
               9        24         2     ...;]
```

An value for `BUSAC_I = 0` indicates that their is no corresponding AC bus in any of the AC systems, e.g. DC bus 7.

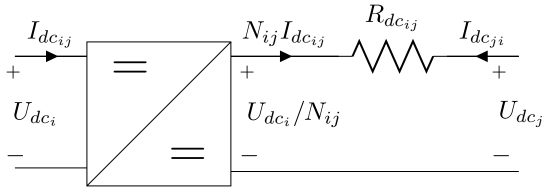


Fig. 4: DC line model with a DC/DC converter.

The set of AC buses can be interconnected by the same AC grid, or can alternatively be part of multiple non-synchronised zones. This can be accomplished by selecting different `ZONE` values in the MATPOWER `bus` matrix. Internally, MATACDC renumbers the buses. Similarly, the option of isolated buses (e.g. offshore wind farms) has been implemented by defining infinite AC buses in the MATPOWER `bus` input matrix.

4.2 DC converters

The `convdc` matrix contains all converter station data, such as losses, impedance values, status flag, control modes. Each converter is connected to a DC bus, of which the `CONV_BUS` numbering corresponds to the `BUSDC_I` numbers defined in the `busdc` matrix. The effect of a converter outage on the power flows in the AC/DC system can easily be adressed by changing the `CONVSTATUS` flag from 1 to 0. Internally, MATACDC handles DC buses without an AC connection differently from buses with a connection. Additionally, a number of named indices are defined for `CONVTYPE_DC` and `CONVTYPE_AC`, depending on the type of control. The different options for the representation of the converter controls are discussed in the next section.

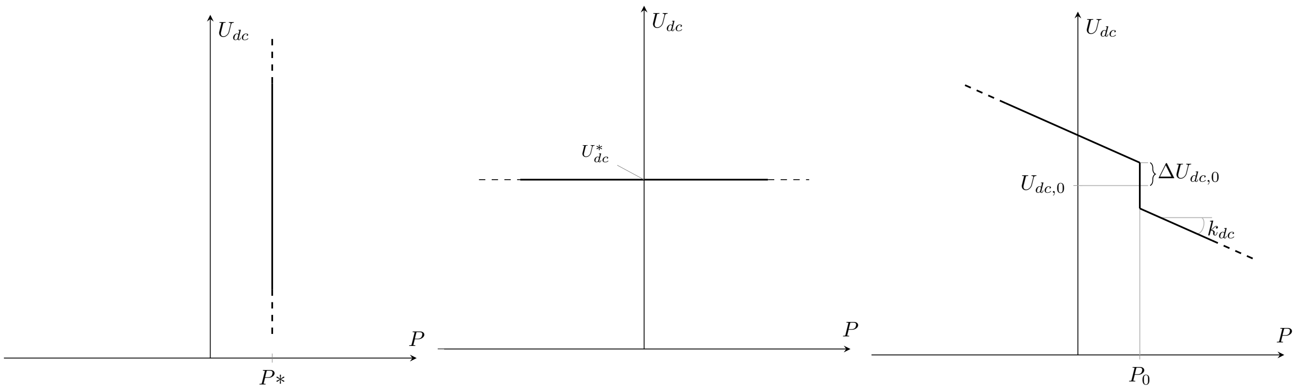
4.3 DC branches

For each connection between DC buses, a branch is created in the DC branch matrix `branchdc`. Similar to a converter, a branch outage can be studied by having `BRDC_STATUS` equal to 0. In the DC system power flow, the only line parameters taken into account are R_{dc}, the resistances of the lines.

4.4 Example: DC/DC converter representation

The MATACDC code has been conceived in a way that it allows a straightforward integration of user-defined models and additions. In this example, it is discussed how a DC/DC converter can easily be added to the program, by making an analogy to the implementation of a combination of a line and a phase-shifting transformer in MATPOWER. First, the theoretical model is presented. Thereafter, the integration in the power flow routines is briefly discussed.

Fig. 4 represents the model of the DC/DC converter and the line, with N_{ij} the voltage ratio between the two sides of the DC/DC converter. The current injections can be written as a



(a) P constant **(b)** U_{dc} constant **(c)** P – U_{dc} droop

Fig. 5: Converter steady-state operation characteristics.

function of the voltages at the two ends as

$$\begin{bmatrix} I_{dc_i} \\ I_{dc_j} \end{bmatrix} = \mathsf{Y}_{\mathsf{dc,ij}} \begin{bmatrix} U_{dc_i} \\ U_{dc_j} \end{bmatrix}, \tag{1}$$

with the DC branch matrix $\mathsf{Y}_{\mathsf{dc,ij}}$ given by

$$\mathsf{Y}_{\mathsf{dc,ij}} = \begin{bmatrix} Y_{dc_{ij}}/N_{ij}^2 & -Y_{dc_{ij}}/N_{ij} \\ -Y_{dc_{ij}}/N_{ij} & Y_{dc_{ij}} \end{bmatrix}. \tag{2}$$

This can be implemented in the `makeYbusdc` routine where the DC system admittance matrix is defined, by replacing the definition for the branch matrix elements `Ytt`, `Yff`, `Yft`, `Ytf` by

```
N = branchdc(:, 8);
Ytt = Ys;
Yff = Ys ./ N.^2;
Yft = - Ys ./ N;
Ytf = - Ys ./ N;
```

in which `Ys` are the line series admittances of the lines. As an example, column 8 of the `branchdc` matrix has temporarily been used to store the voltage ratios, with the default value for N_{ij} equal to 1.

5 HVDC grid control representation

5.1 Defined control options

Each converter can exhibit a number of different control functions. In a VSC, the active and reactive power can be controlled independently. The different steady-state representations used in MATACDC correspond to the actual VSC control options. The software includes 3 different converter representations with respect to the active power and 2 different converter representations with respect to the reactive power.

Fig. 5 shows the $P-U$ steady-state characteristics for the three active power operating modes. These operating mode can easily be changed as discussed below. The corresponding steady state representations are defined as follows:

1. *P constant*: The converter has a constant active power injection P_s into the AC grid (Fig. 5a).
```
>> convdc(..., CONVTYPE_DC) = DCNOSLACK;
>> convdc(..., PCONV) = ...;
```
2. *U_{dc} constant*: The converter controls the DC bus voltage U_{dc} at the converter terminal to a constant value, irrespective of the active power signal. (Fig. 5b)
```
>> convdc(..., CONVTYPE_DC) = DCSLACK;
>> busdc( ..., VDC) = ...;
```
3. *P – U_{dc} droop*: The active power injection into the DC grid P_{dc} depends on the actual value of the DC bus voltage U_{dc} (Fig. 5c). The droop control has set-points for voltage and power, respectively $U_{dc,0}$ and $P_{dc,0}$, has a variable voltage droop k_{dc} and can include a symmetric voltage deadband $\Delta U_{dc,0}$ as depicted in Fig. 5c. The control is mathematically expressed as

$$P_{dc} = P_{dc,0} - \frac{1}{k_{dc}}(U_{dc} - U'_{dc,0}), \tag{3}$$

with

$$U'_{dc,0} = \begin{cases} U_{dc,0}^- & \text{if } U_{dc} \le U_{dc}^- \\ U_{dc} & \text{if } U_{dc}^- < U_{dc} < U_{dc}^+ \\ U_{dc,0}^+ & \text{if } U_{dc}^+ \le U_{dc} \end{cases}, \tag{4}$$

with $U_{dc,0}^- = U_{dc,0} - \Delta U_{dc,0}$ and $U_{dc,0}^+ = U_{dc,0} + \Delta U_{dc,0}$. The setpoints and parameters for the control can be changed by altering the respective elements in the `convdc` matrix:
```
convdc(..., CONVTYPE_DC) = DCDROOP;
convdc(..., DROOP  ) = ...;
convdc(..., PDCSET ) = ...;
convdc(..., VDCSET ) = ...;
convdc(..., DVDCSET) = ...;
```

with the named indices $\cdots$`SET` denoting the setpoints and `DROOP` the droop value k_{dc}.

Similarly, the reactive power operating mode can be changed using `convdc` index `CONVTYPE_AC`. The converter can be represented in MATACDC as a constant reactive power injection into the grid, or a constant voltage controlled AC bus.

5.2 Example: Current-based droop control

MATACDC uses a power-based voltage droop control. The converter representation can however relatively easy be changed to a current-based voltage droop control by using

$$I_{dc} = I_{dc,0} - \frac{1}{k_{dc}}(U_{dc} - U_{dc,0}), \tag{5}$$

leaving out the deadband in the control. Altering the control mode of the converter changes its representation in the power flow routine. In analogy to [8], where the DC system sequential power flow routine was altered to include a power-based droop, we can rewrite the control representation for converter i as

$$I_{dc,0_i}^{(j)} = I_{dc_i}(\boldsymbol{U_{dc}}^{(j)}) + \frac{1}{k_{dc_i}}(U_{dc_i}^{(j)} - U_{dc,0_i}), \tag{6}$$

with

$$I_{dc,0_i} = \frac{P_{dc,0_i}}{pU_{dc,0_i}}, \tag{7}$$

the current reference. The DC current injection for this converter I_{dc_i} can be rewritten as

$$I_{dc_i} = \sum_{\substack{j=1 \\ j\neq i}}^{n} Y_{dc_{ij}} \cdot (U_{dc_i} - U_{dc_j}). \tag{8}$$

The notation from Equation (6) uses the analogy to converge to a certain power injection in a power flow. In this case, these injections are unknown, whilst the current setpoint of the droop $I_{dc,0_i}$ is known prior to the iteration and can hence be used instead.

The current-based droop characteristic can be implemented in the power flow routine by altering the MATLAB function `dcnetworkpf`, in which the DC power flow routine is defined. To do so, a new variable $\boldsymbol{X_{dc}}$ is defined as

```
Xdc        = -Pdc;
Xdc(droop)= -Pdcset(droop)./...
                     (pol*Vdcset(droop));
```

with `pol` denoting p from Equation (7) to take into account the polarity of the grid in the per unit convention. This implies that for the constant power controlled buses, the active powers are used to determine the residues in the iteration, while for the current-based droop control, the current droop setpoints are used. The minus sign stems from convention on the positive direction of the power flow. The values of $\boldsymbol{X_{dc}}$ are now updated each iteration cycle as

```
Pdccalc = pol*Vdc.*(Ybusdc*Vdc);
Xdccalc = Pdccalc;

Idccalc = Pdccalc./(pol*Vdc);
Xdccalc(droop) = Idccalc(droop)+...
  1./VIdroop(droop).*(Vdc(droop)-...
                          Vdcset(droop));
```

The modified Jacobian elements for the current-based droop controlled buses can be determined after substituting Equation (8) in Equation (6) and are given by

```
J(droop,:)    = Ybusdc(droop,:).*...
                (ones(size(droop))*Vdc');
J(drooplidx) = J(drooplidx)+ ...
         1./VIdroop(droop).*Vdc(droop);
```

The incremental changes are solved by having `dXdc = Xdc-Xdccalc;    dV   = J\dXdc;` with \the MATLAB command to solve `J.dV = dXdc`. Also other droop implementations can be accounted for in a similar way by modifying the power flow algorithm.

6 Case study

MATACDC includes different case studies based on a 5-bus AC test system including a 3-terminal DC system from [8] and a modified version of the IEEE RTS test system extended with 2 MTDC systems from [2].

6.1 The CIGRE B4 DC grid test system

As an example, Fig. 6 shows the implementation of a hybrid AC/DC system, namely the CIGRE B4 DC grid test system [9]. The power flow results and inputs are based on the ongoing work in the CIGRE Working Group B4-58. The HVDC networks (depicted in black) consist of a symmetric monopolar link (±200 kV), a meshed 5-terminal bipolar HVDC grid (±400 kV) and a symmetric monopolar radial multi-terminal system with 4 converters (±200 kV). The networks consist of both overhead lines and cables. The three AC networks (depicted in gray) Ba-A0 to Ba-A1, Ba-B0 to Ba-B3 and Bo-C1 to Bo-C2 have operating voltages of respectively 380 kV, 380 kV and 145 kV. Buses Ba-A0, Ba-B0 and Bo-C1 have been chosen as the AC slack nodes for the different AC grids. The converter control modes, setpoints, loss model and other data are taken from [9].

The DC/DC converters has been modelled as a constant voltage ratio to obtain a steady-state power flows of respectively 600 MW for the converter between Bb-B1 and Bb-B1s and 300 MW for the converter between Bm-E1 and Bb-E1. The AC buses Bo-D1, Bo-E1 and Bo-F1 have been modeled as infinite buses.

In this example, the program needs three overall iterations to converge. When the AC grid is left out of the analysis by replacing all AC converter buses by infinite buses, the execution time roughly changes to about 74%.

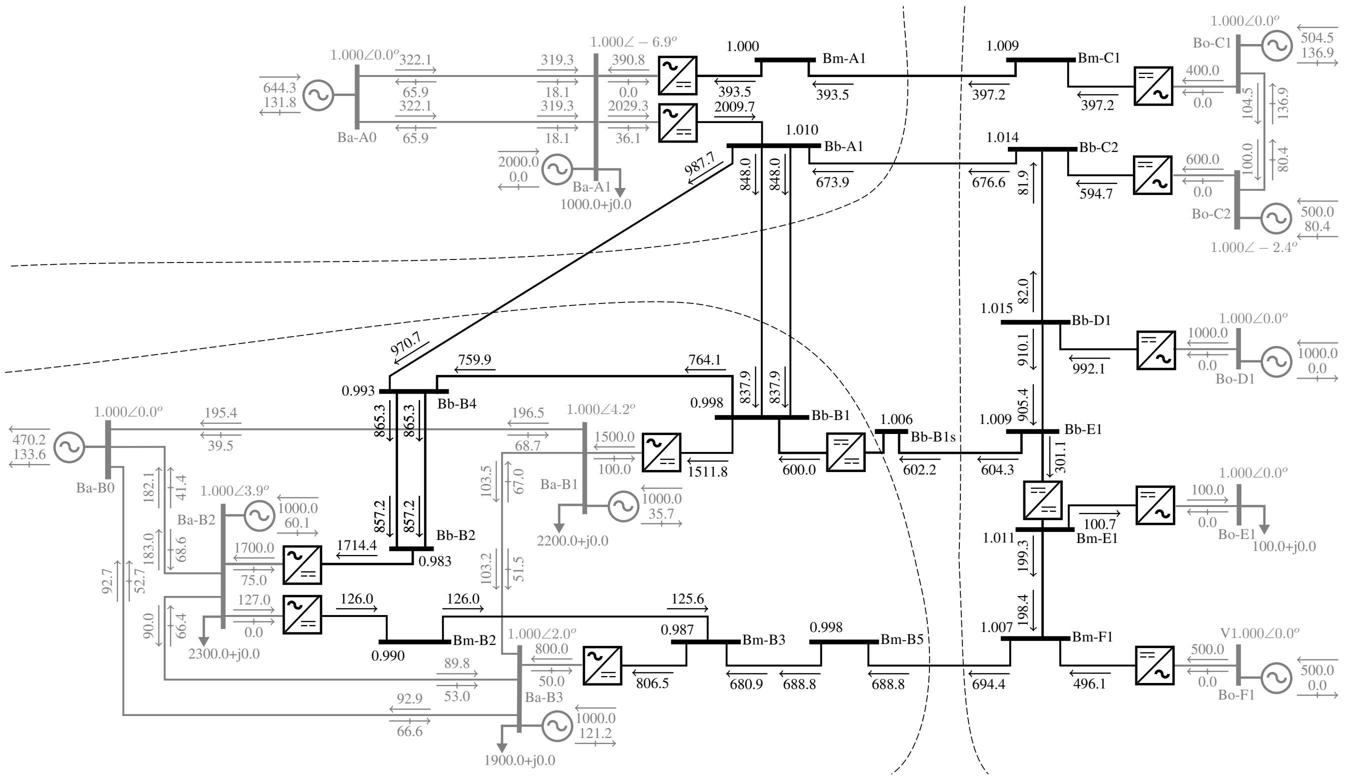


Fig. 6: Power flows in CIGRE B4 DC grid test system. **Legend**: → Active power (MW) and ↛ Reactive power (MVAr).

6.2 Converter outage analysis

Next, the effect of different control modes on the power flows and voltage deviations are investigated by analysing the steady-state operation of the power system after a contingency. More specifically, the effect of an outage of converter Cb-B2 (connected between DC bus Bb-B2 and AC bus Ba-B2) is considered for two different control options. The focus of the analysis is on the change of the voltages and power flows in the HVDC system.

The first control option considers the converter connected to Bm-A1 under constant DC voltage control (slack node) and the AC/DC converters connected to Bm-C1, Bb-C2, Bb-D1, Bm-E1 and Bm-F1 as constant active power injection (e.g. offshore wind farms and offshore load). All remaining converters have a power-voltage droop. Figs. 7–8 respectively show the power flows and voltages after the outage and the differences in power flow and voltage as a result of the contingency and the control actions. The differences in power flow (compared to Fig. 6 provide information on the power sharing after the outage and the voltage differences in the system that determine and influence this power sharing.

The second case (Figs. 9–10) differs from the first by having a constant voltage representation for converters Cb-A1 and Cm-B2, the converters respectively connected to DC buses Bb-A1 and Bm-B2.

A general observation is that the DC voltage profiles changes most at the bus of the converter facing the outage. This voltage deviation spreads through the system and is most pronounced in the vicinity of the contingency. This large local deviation caused by the outage in combination with voltage droop control buses makes that the nearby converters (at buses Bb-A1 and to a lesser extent Bb-B1) take the largest share in power. The HVDC grid with local droop control thus has a tendency to solve deficits locally. In case of a constant voltage control at bus Bb-A1 (Figs. 9–10), the converter clamping the voltage takes a far higher share of the power at the cost of the droop controlled converter at bus Bb-B1. The closer the voltage controlling converter is located to the contingency, the more this observation holds.

Even more pronounced in this respect is the limited contribution of the remote converters at DC buses Bm-B2 and Bm-B3 in the radial DC system, which is connected to the rest of the DC system by means of a DC/DC converter. Comparing the contributions from Cm-B2 and Cm-B3 in Figs. 7–8, it is observed that Cm-B3 takes a higher percentage of the power, which is due to the combination of a higher droop gain and the fact that the converter is electrically closer to the faulted converter.

In the case of droop controlled converters (Figs. 7–8), the outage results in a small overloading of the line between Bm-B5 and Bm-F1 (line rating equal to 1962 A, with line current of 2075 A) in the radial DC system due to the contribution of the converters in this subsystem to evacuate the offshore power to

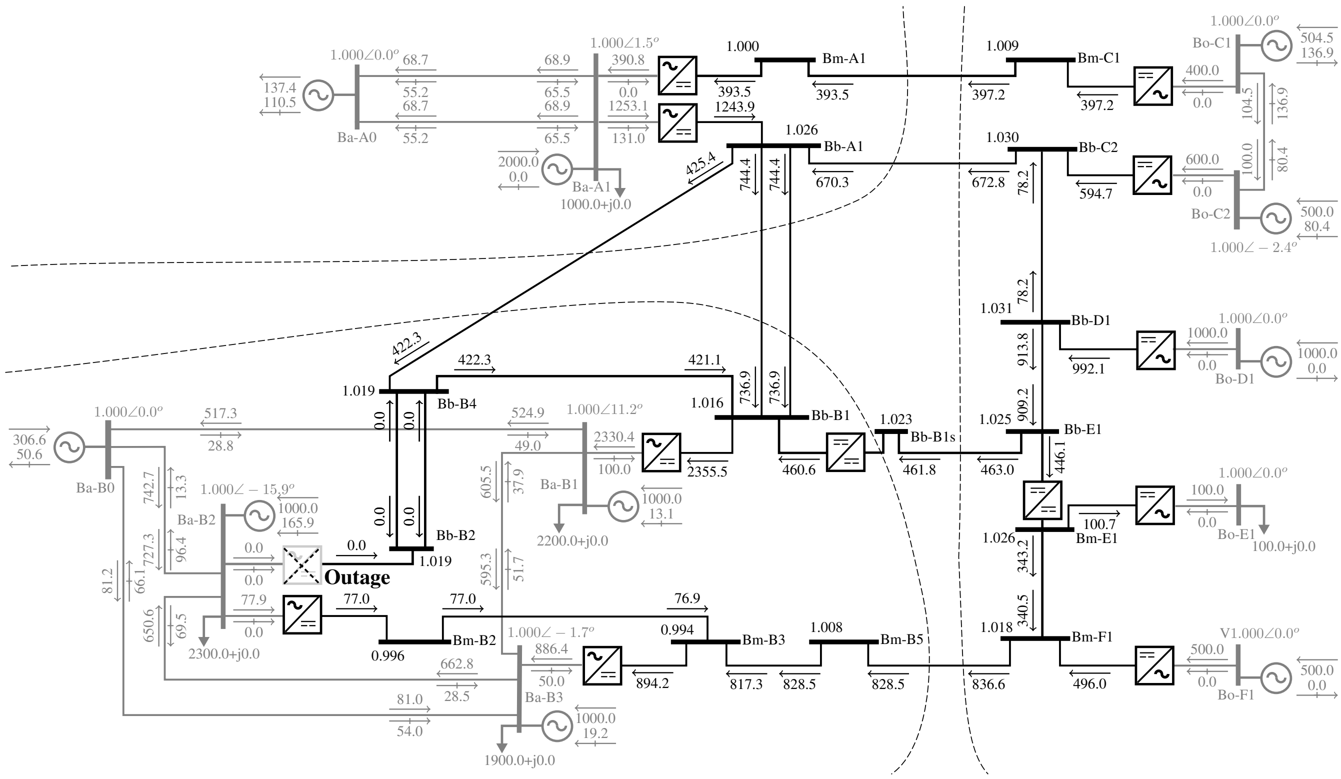


Fig. 7: Power flows in CIGRE B4 DC grid test system after outage of converter Cb-B1 (bus Bb-B1) – droop control.

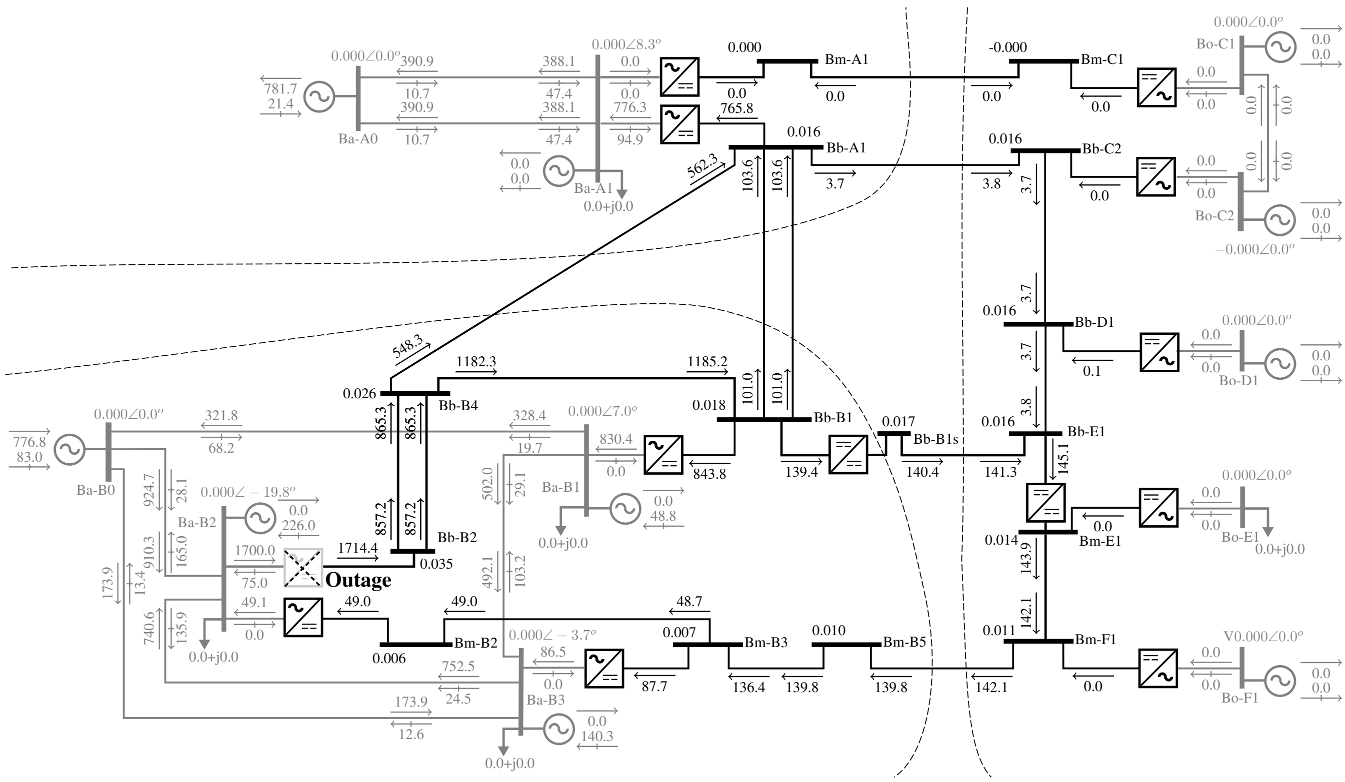


Fig. 8: Power flow and voltage differences in CIGRE B4 DC grid test system after and before the outage of converter Cb-B1 – droop control.

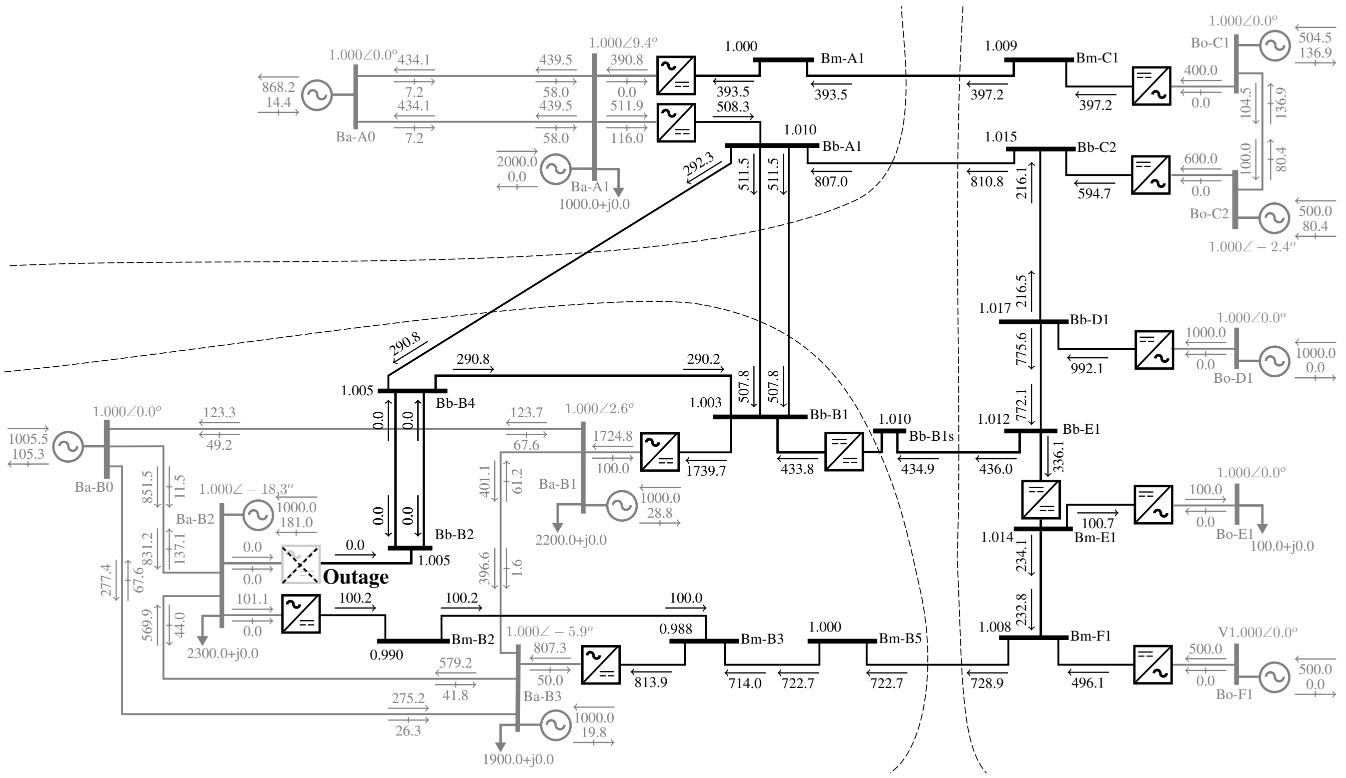


Fig. 9: Power flows in CIGRE B4 DC grid test system after outage of converter Cb-B1 (bus Bb-B1) – droop control with constant voltage control in Cb-A1 and Cm-B2.

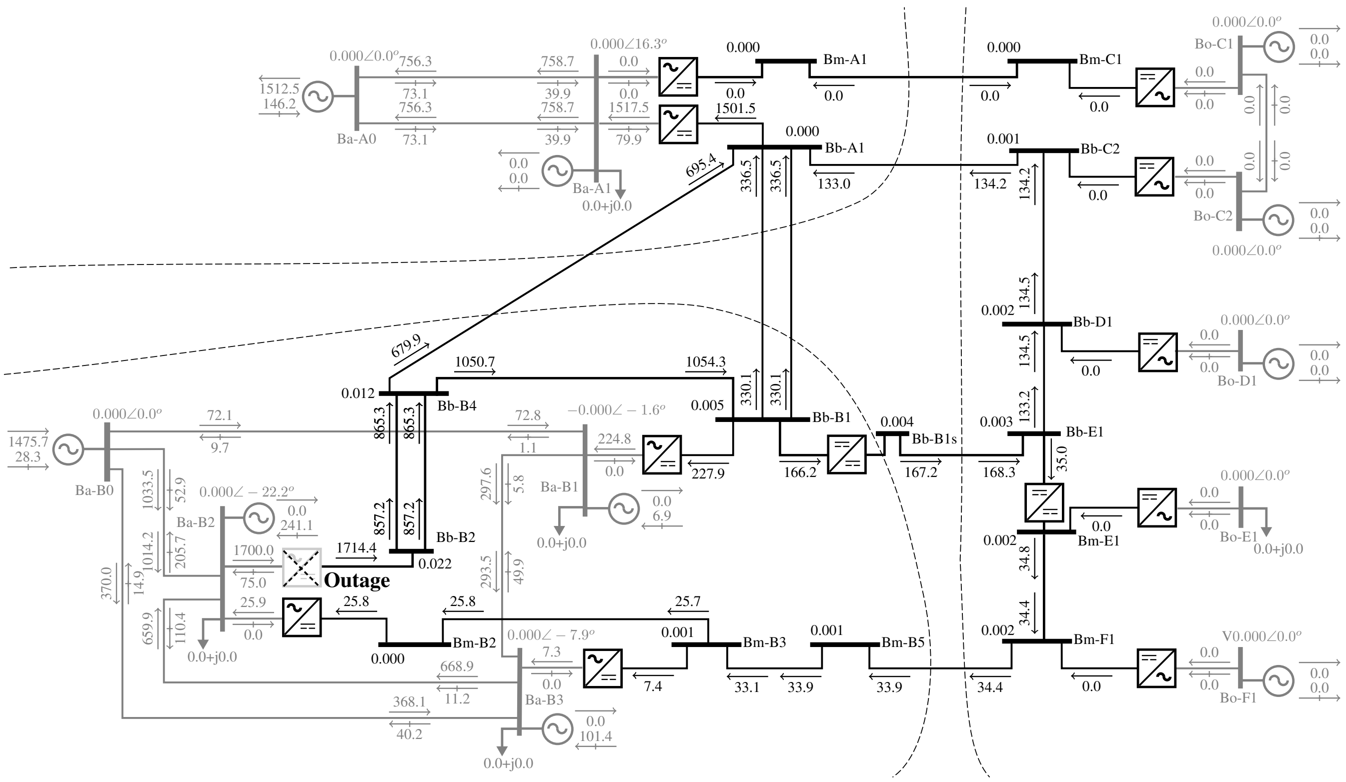


Fig. 10: Power flow and voltage differences in CIGRE B4 DC grid test system after and before the outage of converter Cb-B1 – droop control with constant voltage in Cb-A1 and Cm-B2.

the onshore AC system. The overload is not present in the case of constant voltage control in converter Cm-B2 (Figs. 9–10). This is due to the fact that, in case of a constant voltage control in Cm-B2, not much power is needed to clamp the voltage at Bm-B2, while the constant voltage control at the same time makes that also in the vicinity of this converter, the voltage change is mitigated. On the contrary, in case of a droop control, the voltage profile in the radial DC system turns out to be more affected by the outage of Cb-B2, which makes that a higher power share is taken by the converters, causing an overload of the line.

An important aspect that has been left out of the analysis is the control of the DC/DC converter, which can largely influence the contribution to the power sharing amongst the different subsystems. A similar remark can be made with respect to power flow changes in the AC systems.

7 Conclusion

In this paper, the open source power flow program MATACDC was presented. Simulation results on the CIGRE DC grid test system show that the program can be used to study interactions in complex hybrid AC/DC power systems. The results show that, in case of a converter outage, the voltage deviation, which determines the control response, spreads through the system and is most pronounced in the vicinity of the converter facing an outage. This large local deviation caused by the outage, in combination with voltage droop control buses, makes that the nearby converters tend to take a larger share of the power. When the system has constant voltage buses in the vicinity of the converter facing the outage, such converters tend to take a greater part of the power deficit caused by the outage.

Acknowledgements

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